Improved Tools for Drought Planning
Final Report

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1 Introduction

1.1 Project Description

As research on climate variability and climate change continues to expand, cities and states in the western United States are setting guidelines for drought preparedness. And although the scientific community agrees that human-induced climate change is occurring, tree-ring research shows that in the last 780 years there have been 13 droughts in the Colorado River basin lasting from 15 to greater than 20 years[1]. There is potential for severe drought in the 21st century on the Colorado River and the Salt and Verde River watersheds, whether due to normal climatic variations indicated in the tree-ring record or due to human-induced climate change. Further, central Arizona has seen water shortages on the Colorado, Salt, and Verde Rivers in the last 9 years. It is essential for the long-term sustainability of municipalities and Indian communities in Arizona to address strategies for collective management of surface water and groundwater in the event of these conditions.

This project brought together the East Valley Water Forum (EVWF), the Arizona State University Decision Theater (DT) and the University of Arizona (U of A) Tree-Ring Laboratory. The purpose was to integrate tree-ring research from the University into the EVWF drought scenario planning through the design of groundwater modeling scenarios in drought conditions. These scenarios could then be visualized through a tool developed by the DT.

1.2 Statement of Need

Arizona's water managers are well aware of the potential for severe drought. The EVWF is a partnership of 25 tribal, public, and private water agencies and interested stakeholders involved in water resource management in the East Salt River Valley of Arizona. The results of the first phase of their planning are compiled in their Management Plan and was completed in 2007. Even in the early stages of developing a regional groundwater management plan, East Valley water providers recognized that drought scenario planning was an important and necessary component. However, due to the many variables involved in this type of scenario planning, such as climatology, water conservation, and shifts in supply and demand related to drought conditions, the EVWF determined this would be better suited as a second phase to the regional planning effort. The development of drought scenarios, their next phase of regional planning, will consider climatology research dating back nearly 800 years to be incorporated to hydrologic groundwater modeling. The results of this modeling will enable the EVWF participants to discuss various responses to drought impacts through effective water resource management.

[1] Gray, S.T., Bettancourt, J.L., Fastie, C.L., and Jackson, S.T., Patterns and sources of multidecadal ocillations in drought-sensivitve tree-ring records from the central and southern Rocky Mountains, *Geophysical Research Letters*, 30(6), pp.49-49, 2003.

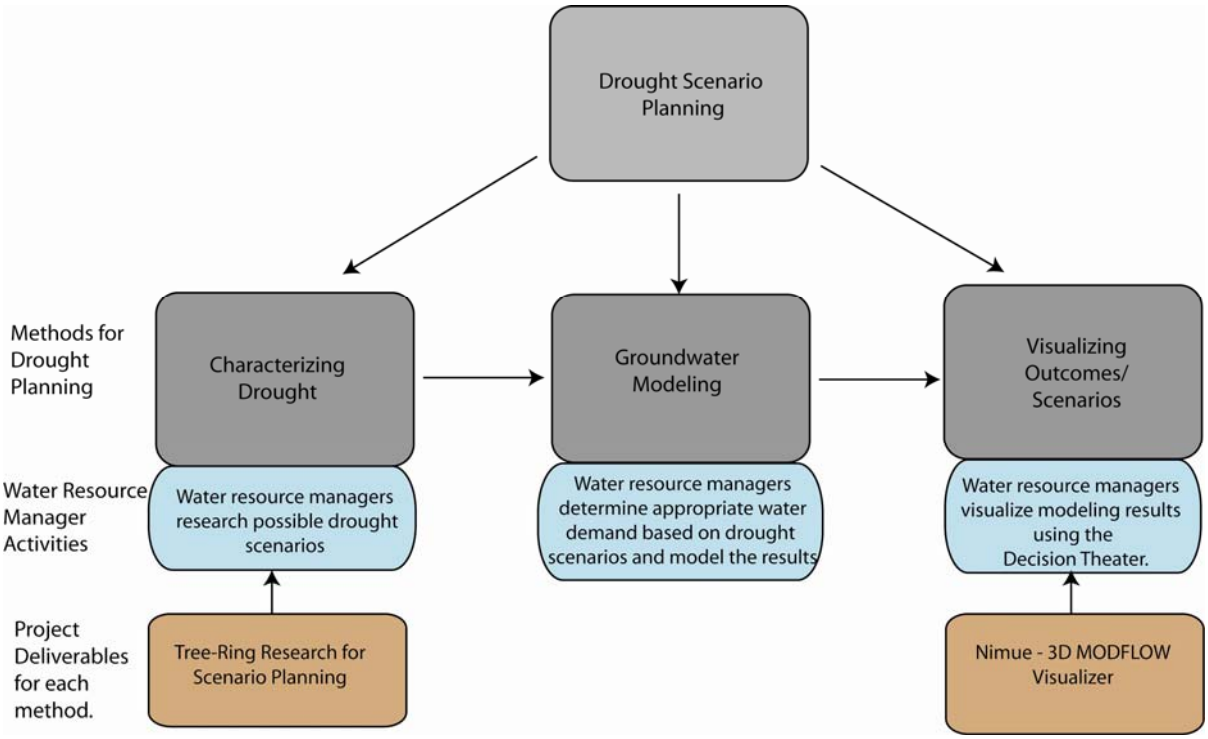
Strategically, this project is important in the following areas:

- Water Resource Management: Water infrastructure is expensive to build and maintain. Regional drought scenario modeling and planning will provide needed information to enable water managers to explore cooperative uses of existing infrastructure and water resource management during drought conditions.
- Drought Scenario Planning Research: We are merging climatology, visualization, and hydrology into an integrated scientific solution for assessing drought issues.
- Technical Assistance: The software toolkit and documentation will provide assistance to any regional planning group addressing drought issues in the CAP service area.

1.3 Project Drought Scenario Planning Methodology

The diagram below illustrates the three steps in the Uof ATree-Ring Lab/EVWF/DT drought scenario planning methodology. Drought scenario planning begins with drought characterization. This step involves the water resource manager's research and development of possible drought scenarios, including consideration of historic tree-ring research. These scenarios are in turn used to perform the next sequential step, groundwater modeling. In this step, the water resource managers determine appropriate water demand and estimate available groundwater supplies based on the drought scenarios, producing a time-stepped groundwater model output. The final step allows visualization of the groundwater model for the various time increments specified. The groundwater basin is displayed using *Nimue*, an open-source 3D visualizer developed by DT that accepts MODFLOW 2000 free-format files. *Nimue* was developed to allow groundwater modeling display within the DT, hosted on its high performance computers. But Nimue also provides a free, lightweight groundwater modeling desktop viewer that allows various water resource managers to quickly observe data without the need to purchase expensive MODFLOW viewing tools.

This figure depicts the project deliverables and the interaction of the water resource maangers at each phase.


Drought Scenario Planning
Methods for Drought Planning
Characterizing Drought
Groundwater Modeling
Visualizing Outcomes/ Scenarios
Water Resource Manager Activities
Water resource managers research possible drought scenarios
Water resource managers determine appropriate water demand based on drought scenarios and model the results
Water resource managers visualize modeling results using the Decision Theater.
Project Deliverables for each method.
Tree-Ring Research for Scenario Planning
Nimue - 3D MODFLOW Visualizer

This final report describes the presentations, products, and collaboration between the U of A, ASU, and the EVWF with the deliverables listed in the attached CD and appendices.

2 Project Execution

2.1 Project Approach

Over the past two years, the EVWF has worked with the Arizona Department of Water Resources (ADWR) to simulate future East Salt River Sub-basin groundwater elevations using the ADWR Salt River Valley groundwater model. In this first phase of regional planning, the EVWF developed 3 groundwater scenarios based on water availability during non-drought conditions that were modeled by ADWR, and then visualized at the DT. In this project, the EVWF is developing Phase II of the regional planning effort, involving scenario development of drought conditions and analysis of the effects of these drought conditions on the East Salt River Valley Sub-basin groundwater aquifer.

At the onset of this project, we intended the project workflow to consist of three phases under the contract awarded 11/4/06:

Phase 1. A documented process for considering tree-ring records in developing drought scenarios
Phase 2. A scenario modeling component in which parametric data are adjusted using MODFLOW
Phase 3. Creation of display software, with associated documentation, that visualizes MODFLOW modeling results.

Our goal was to host several meetings wherein the U of A, ASU, and EVWF could develop the project. Due to budget and scheduling conflicts, continuous active participation between the EVWF and Hirschboeck was curtailed. However, the EVWF is considering incorporating the tree-ring research from Dr. Hirschboeck's group into the development of drought scenarios for groundwater modeling. This collaboration will continue beyond the funding of this AWI grant. Hirschboeck met with the DT and some EVWF drought group members in the fall of 2007, where she presented the results from her report, "A Tree Ring Based Assessment of Synchronous Extreme Streamflow Episodes in the Upper Colorado and Salt-Verde-Tonto River Basins", which are currently being considered in the EVWF drought scenario planning effort.

As a result of these changes, the scope of the project was adjusted to provide water resource managers presentations both at the DT and off-site and also produced the following deliverables under MOU dated 1/31/07:

1. A guideline for generating scenarios of drought conditions using tree-ring information (See Appendix A). This product, designed by Dr. Katherine Hirschboeck from the University of Arizona Tree-Ring Laboratory, is contained in a website for easy access to the water resource managers of the EVWF as well as others.

2. Groundwater visualization software designed by Dr. Perry Miller of the ASU DT and his team (See attached CD).
3. A software manual that describes how to install and run the software package for water users (See Appendix B).

A description of the project presentations and supporting deliverable products developed under funding by the Arizona Water Institute are described in the following sections.

2.2 Project Presentations

The EVWF utilized *Nimue* to present the scenario results of their Management Plan to an educational forum, two East Valley city councils, and another water organization. (see pictures below). The visualization software's versatility was demonstrated by its ability to display the groundwater modeling both within the DT drum as well as at off-site presentations. Visualizing the groundwater modeling proved to be a successful medium for generating scientific discussion that was facilitated by the improved tools funded through this grant. The EVWF management plan results were presented to water providers, which showcased the EVWF accomplishments and its standing as a progressive water resource management group.

101
202
10

2.3 Guideline for Drought Condition Scenarios Generation

The main objective of this aspect of the project was to provide a framework for the use of tree-ring data in creating drought scenarios for water managers. Originally, a standard set of guidelines for determining drought scenarios based on tree-ring records was envisioned. As the project developed, however, it became apparent that a single set of guidelines would be too constraining. The project was re-focused on the deliverable of an accessible web-based "framework" that could display one or more tools to use in scenario development. The resulting web resource titled "**A Framework for Generating Exploratory Scenarios of Drought Conditions Using Tree-Ring Information"** is meant to be viewed as an evolving platform that will eventually combine with similar efforts in other regions (e.g., under NOAA "Coping with Drought" initiatives). To see the information, visit the webpage at http://fp.arizona.edu/kkh/awi/awi.htm.

Tree-ring reconstructions are most useful for generating so-called *Exploratory Scenarios*, which "describe the future according to known processes of change and extrapolations from the past by incrementally progressing through time. They rely on logical induction, by using clues from the past and present and working out the pathways that the future may take." (SAHRA Scenario Development Group webpage: http://www.sahra.arizona.edu/scenarios/content/blogcategory/13/30/)

There are two ways in which tree rings can be used in exploratory scenario development: (1) by providing information on the full range of past patterns of climate and streamflow behavior (*projective scenarios*), and (2) by using past climate and streamflow behavior as a baseline from which to construct alternative processes or patterns that significantly vary from the past, e.g., under future climate change (*prospective scenarios*). This phase of the project addressed possible ways in which tree-ring reconstructions of streamflow could be used in both projective and prospective scenario approaches. By focusing on reconstructed streamflow as the key variable of interest, it was assumed that the magnitude and variability of surface water supplies are key inputs needed in developing drought management scenarios and groundwater management plans. The approach used was to extract a series of multiyear sequences of flow from long term tree-ring reconstructions of streamflow. These streamflow sequences can then be used as possible input into surface/groundwater models to illustrate different modes or patterns of streamflow that have been experienced in the past (*projected scenarios*), or may be experienced in the future (*prospective scenarios* via altered magnitudes, frequency, persistence, or amplitude).

The website's framework organizes the information needed for this approach. In addition to links and relevant background material on tree rings and reconstruction methods, the website provides access to data spreadsheets, descriptive statistics and visualizations of streamflow reconstructions for the Upper Colorado and Salt-Verde-Tonto River Basins. (NOTE: The reconstructions were produced during an earlier project titled: A Tree-Ring Based Assessment of Synchronous Extreme Streamflow Episodes in the Upper Colorado & Salt-Verde-Tonto River Basin.")

Seventeen multiyear sequences of past streamflow covering different time frames (30-year, 20-year, 11-year, and 7-year) were selected from the reconstruction data for possible use by water mangers in exploratory scenario development and planning for future drought conditions. An effort was made to select sequences that represent the full range of past (and possible future) streamflow behaviors, including severe and sustained low flow sequences, high flow episodes, and periods with high amplitude variability. The sequences are displayed with suggestions for how they might be used as input for projective and prospective exploratory scenarios. A Streamflow Sequence Data Spreadsheet is available for downloading and contains the reconstructed flow data, quantile visualizations, and graphs for each sequence. Users can use the spreadsheet to select, plot, and/or analyze additional sequences if desired.

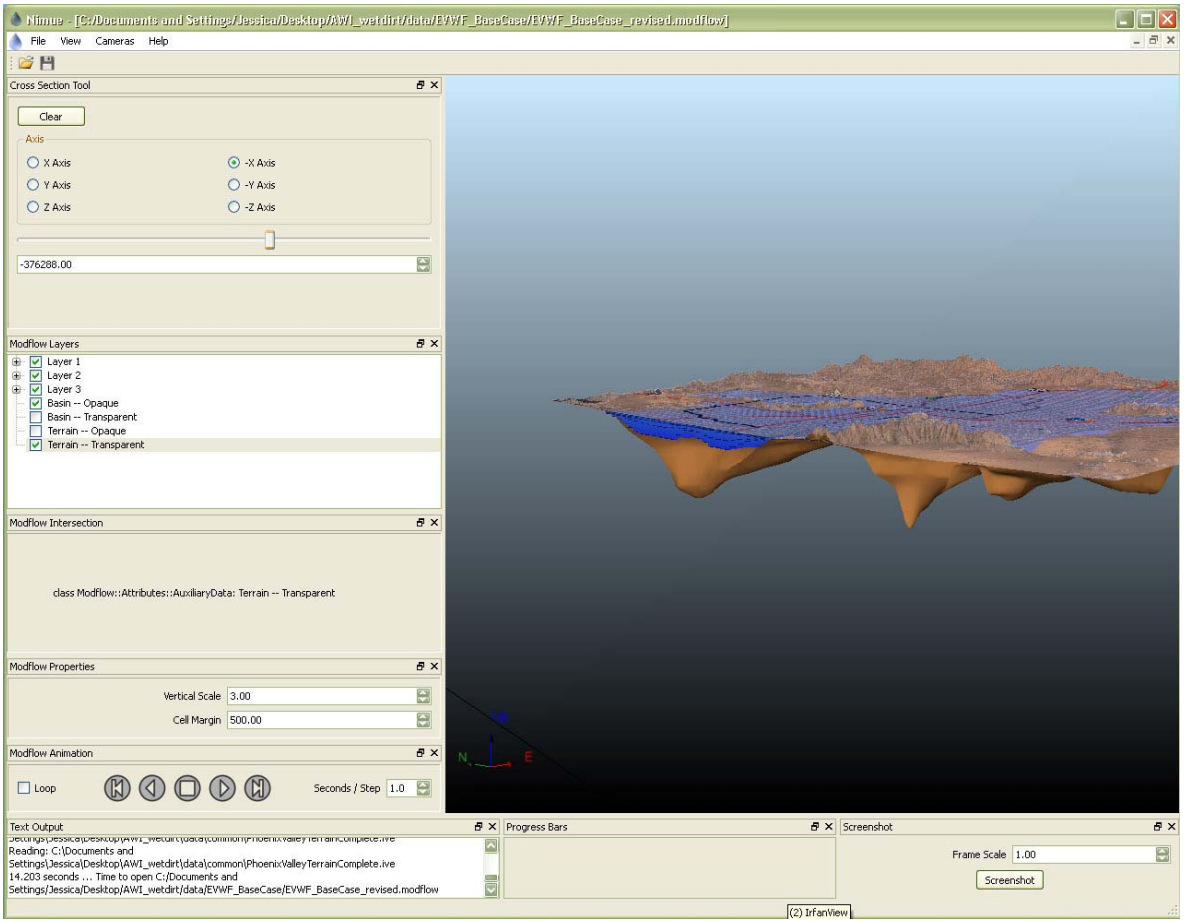
Ongoing and future collaborations with water managers will provide the opportunity to evaluate the usability and applicability of this framework for drought scenario development. This webpage can be expanded to meet the needs of the EVWF in their examination of various management scenarios under drought conditions.

See Appendix A for more details on the website.

2.4 Groundwater Visualization Software

Software for Enhanced Understanding of groundwater data

Nimue (pronounced nee-moo-ay) has been designed to view groundwater data produced by MODFLOW (MODular three-dimensional finite-difference ground-water FLOW model), a software modeling tool written by the USGS to simulate the flow of groundwater. Although there are several software products that are capable of viewing MODFLOW data, they are typically designed for use by hydrologists and engineers. *Nimue* is a lightweight application specifically designed for the visualization of the relevant scientific information needed by water resource managers. Additionally, *Nimue* is open source, free, and compatible with the DT such that groundwater data can be viewed immersively in 3D as well as on a user's desktop. Open source software allows the executable and its source code to be freely distributed, allowing outside developers to update and enhance the existing code to meet their own needs. This promotes future, tailored development for visualization software that can view additional datasets.



Screenshot of Nimue

The DT's visualization environment, known as "the drum," is a politically neutral location for hosting water resource managers that are attempting to reach consensus on regional natural resource issues. The benefit of *Nimue* is that it is easy for decision makers to review groundwater data in their own office and also view data using the same framework in stereo (3D) in the DT when collaborating with other decision makers.

The principal features that set this software apart from other MODFLOW post-processors are

1) the maximum leveraging of modern, immersive 3D-graphics capabilities
2) the ability to put the results in context by adding additional (geospatial) data to the scene
3) it is free and open source.

Other key features included in Nimue are:

- Easy viewing and navigation in three dimensions of MODFLOW data
- Ability to import geographic data
- Animation feature runs through time steps of data
- Interactive cross-section generation that cuts across data surfaces
- Convenient creation of 3D data fly-through
- Quick export of images from viewer

See CD and Appendix B: User Manual for installation and operating instructions. Consult the user manual to learn more about the MODFLOW file types and formats that can be read by *Nimue.*

2.5 Groundwater Visualization Software Manual

The user manual for *Nimue* describes its installation, importation of groundwater data, and available functions for viewing groundwater data. See Appendix B for the full manual.

3 Results

This project's success is demonstrated through the formation of new working relationships that were created through collaborative efforts and the facilitation of groundwater modeling visualization that fostered discussions. Future work will allow for further investigation of incorporation of tree-ring analysis into the drought scenario planning process. The tools developed under funding by this grant have equipped the DT and EVWF for viewing drought scenario data when the EVWF has completed Phase II of their groundwater modeling.

3.1 New Relationships

New relationships were fostered through this Arizona Water Institute grant. It is expected that the EVWF will continue collaborating with Dr. Hirschboeck and her team when necessary to include tree-ring research in their drought scenario planning. The EVWF is considering tree-ring research into the creation of water management scenarios under various drought conditions. The U of A Tree-Ring Lab and the DT now work together to deliver their products to water resource managers, and the DT has benefited from the expanded knowledge of published as well as in-progress work by the Tree-Ring Lab.

The webpage designed by Dr. Hirschboeck can be expanded to meet the needs of the EVWF in their examination of various management scenarios under drought conditions. Toward this end, Katie Hirschboeck will continue to collaborate with the EVWF as needed as a principle investigator with the Climate Assessment of the Southwest (CLIMAS) program. Designed as a platform which can be augmented and expanded, this webpage is also intended to serve as a regional resource for the Southwest and eventually become one of several components of a proposed "TreeFlow" webpage and paleo toolkit project that will cover the entire Western United States (in collaboration with Connie Woodhouse, Univ. of Arizona, WWA and CLIMAS). See Appendix A for more details on the website.

The cooperation with Hirschboeck and DT has cultivated a setting for improved tools for drought scenario planning by first better understanding historical data and second through immersive visualization of scientific information, which allows water providers to better understand coupled relationships and impacts of water resource management decisions.

3.2 Facilitation of Groundwater Modeling Discussions

The photograph shown below illustrates the DT's ability to present 3D information to water resource managers in a politically neutral environment that facilitates thoughtful, scientific discussion. The screen real estate provides a medium that allows for the display of detailed information, but enough of a canvas to also frame a context for the problem. Thus the groundwater model of the entire Salt River Valley Sub-basin can be seen while still being able to examine individual model cells.

The user-friendly nature of the *Nimue* software affords EVWF the ability to create data for future presentations. EVWF is comprised of a diverse group of water resource managers, each water provider and agency needing to demonstrate different aspects of the scenario results. They now can generate these views for themselves.

3.3 Future Work- Integration of Tree-Ring Information

The outline of tree-ring scenario development generated in this project is the beginning of the practical use of this academic research by water resource managers. It is a template that can now be expanded through future funding. Although the EVWF drought scenario planning is a work in progress, these collaborations will continue beyond the time span of this grant. Additional in-kind funds from the EVWF are reserved for the viewing and analysis of the drought scenarios within the DT using *Nimue*. This project has successfully improved collaboration among universities, agencies, and water resource managers in Arizona. Visualizing the science has enhanced collaboration through an understanding of the science coupled with water resource management.

Appendix A

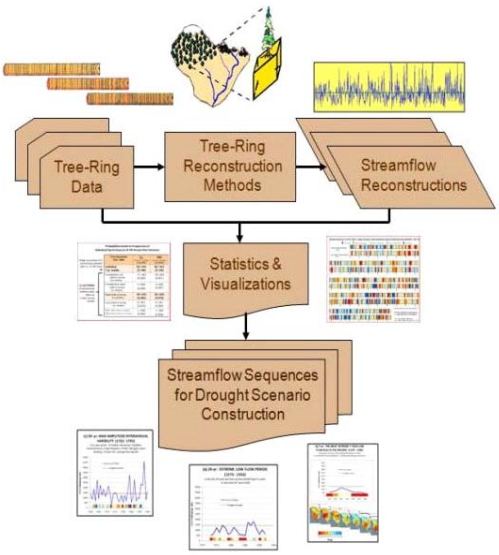
Improved Tools for Drought Planning and Management

A Framework for Generating Exploratory Scenarios of Drought Conditions Using Tree-Ring Information

"EXPLORATORY SCENARIOS describe the future according to known processes of change and extrapolations from the past by incrementally progressing through time."
SAHRA Scenario Development Group

This site provides a compilation of information to aid in the construction of exploratory scenarios of drought conditions in the Southwest through the use of tree-ring based streamflow reconstructions of the Salt-Verde-Tonto and Upper Colorado river basins.

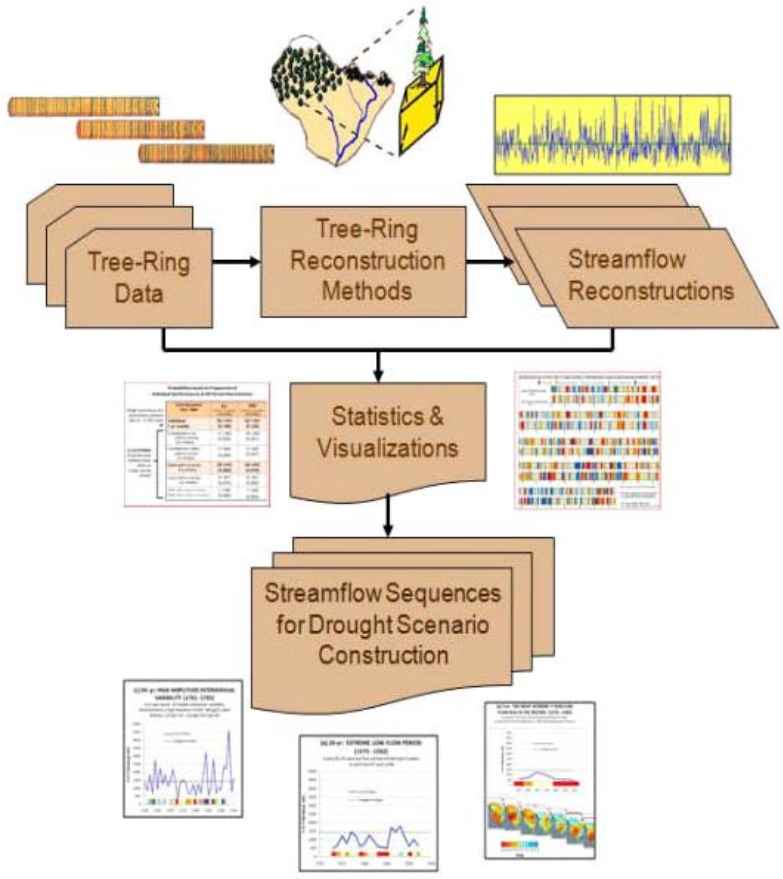
OVERVIEW



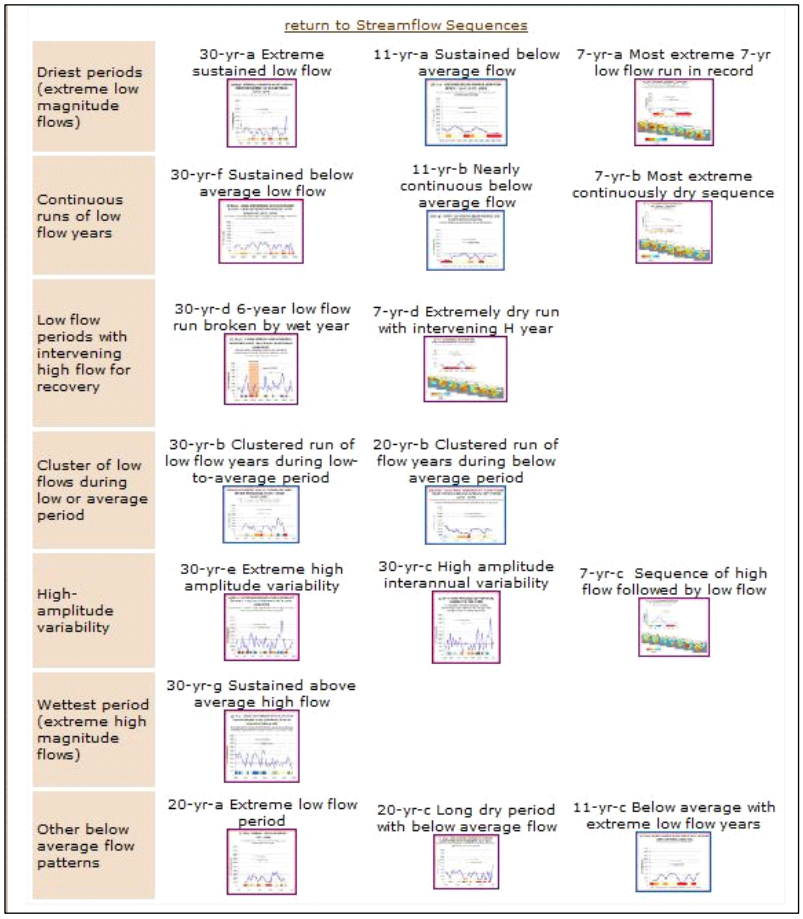
Overview • About Scenario Development • Tree-Ring Data • Reconstruction Methods
Streamflow Reconstructions • Statistics & Visualizations • Streamflow Sequences

The Laboratory of Tree-Ring Research, The University of Arizona | Decision Theater, Arizona State University | East Valley Water Forum | Arizona Water Institute

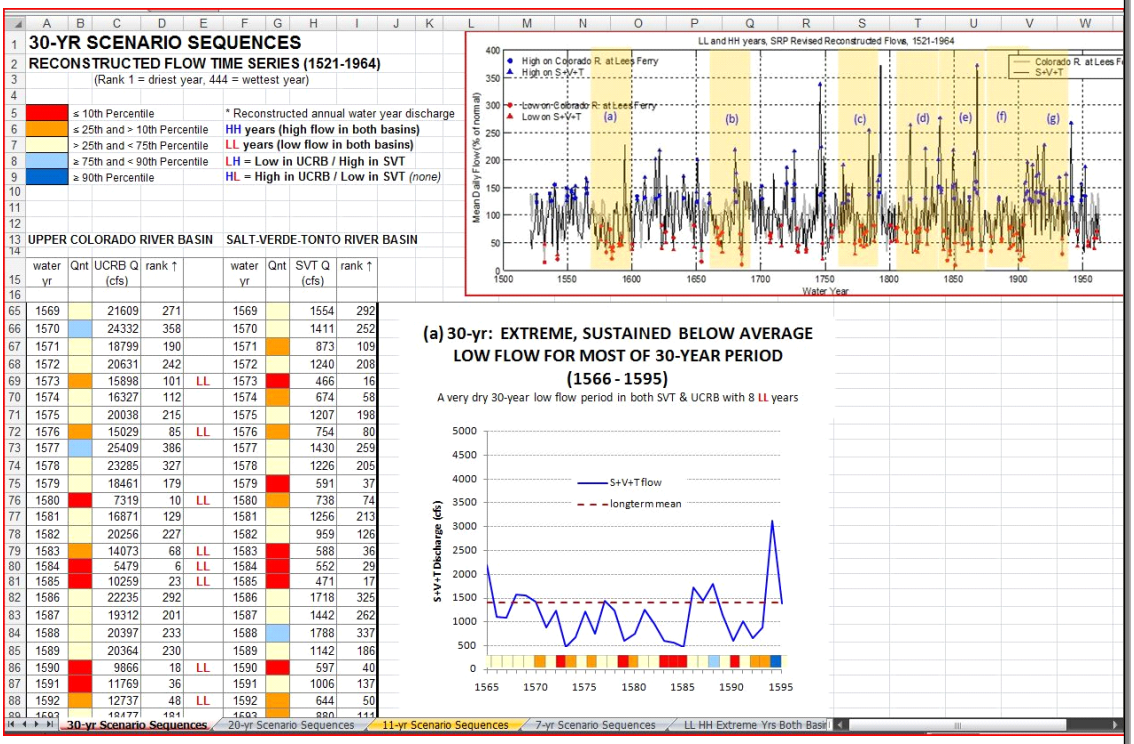
The basic framework for using tree ring information to provide input on past events to develop exploratory scenarios



Suggested uses of the Streamflow Sequences in Exploratory Scenarios


return to Streamflow Sequences
Driest periods (extreme low magnitude flows)
30-yr-a Extreme sustained low flow
11-yr-a Sustained below average flow
7-yr-a Most extreme 7-yr low flow run in record
Continuous runs of low flow years
30-yr-f Sustained below average low flow
11-yr-b Nearly continuous below average flow
7-yr-b Most extreme continuously dry sequence
Low flow periods with intervening high flow for recovery
30-yr-d 6-year low flow run broken by wet year
7-yr-d Extremely dry run with intervening H year
Cluster of low flows during low or average period
30-yr-b Clustered run of low flow years during low-to-average period
20-yr-b Clustered run of flow years during below average period
High-amplitude variability
30-yr-e Extreme high amplitude variability
30-yr-c High amplitude interannual variability
7-yr-c Sequence of high flow followed by low flow
Wettest period (extreme high magnitude flows)
30-yr-g Sustained above average high flow
Other below average flow patterns
20-yr-a Extreme low flow period
20-yr-c Long dry period with below average flow
11-yr-c Below average with extreme low flow years

Streamflow Sequence Spreadsheet, showing a 30-yr sequence selection



30-YR SCENARIO SEQUENCES

RECONSTRUCTED FLOW TIME SERIES (1521-1964)

(Rank 1 = driest year, 444 = wettest year)

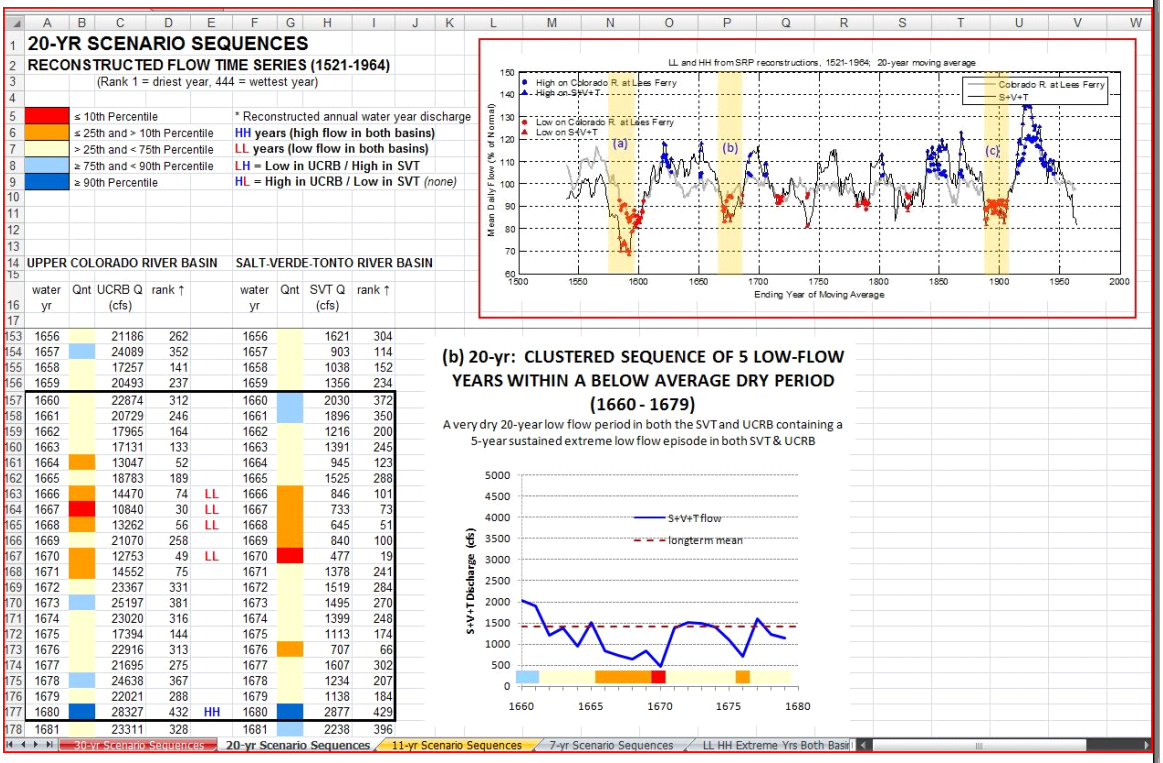
≤ 10th Percentile	* Reconstructed annual water year discharge
≤ 25th and > 10th Percentile	HH years (high flow in both basins)
> 25th and < 75th Percentile	LL years (low flow in both basins)
≥ 75th and < 90th Percentile	LH = Low in UCRB / High in SVT
≥ 90th Percentile	HL = High in UCRB / Low in SVT *(none)*

UPPER COLORADO RIVER BASIN					SALT-VERDE-TONTO RIVER BASIN			
water yr	Qnt	UCRB Q (cfs)	rank ↑		water yr	Qnt	SVT Q (cfs)	rank ↑
1569		21609	271		1569		1554	292
1570		24332	358		1570		1411	252
1571		18799	190		1571		873	109
1572		20631	242		1572		1240	208
1573		15898	101	LL	1573		466	16
1574		16327	112		1574		674	58
1575		20038	215		1575		1207	198
1576		15029	85	LL	1576		754	80
1577		25409	386		1577		1430	259
1578		23285	327		1578		1226	205
1579		18461	179		1579		591	37
1580		7319	10	LL	1580		738	74
1581		16871	129		1581		1256	213
1582		20256	227		1582		959	126
1583		14073	68	LL	1583		588	36
1584		5479	6	LL	1584		552	29
1585		10259	23	LL	1585		471	17
1586		22235	292		1586		1718	325
1587		19312	201		1587		1442	262
1588		20397	233		1588		1788	337
1589		20364	230		1589		1142	186
1590		9866	18	LL	1590		597	40
1591		11769	36		1591		1006	137
1592		12737	48	LL	1592		644	50

(a) 30-yr: EXTREME, SUSTAINED BELOW AVERAGE LOW FLOW FOR MOST OF 30-YEAR PERIOD (1566 - 1595)

A very dry 30-year low flow period in both SVT & UCRB with 8 LL years

Streamflow Sequence Spreadsheet, showing a 20-yr sequence selection



20-YR SCENARIO SEQUENCES

RECONSTRUCTED FLOW TIME SERIES (1521-1964)

(Rank 1 = driest year, 444 = wettest year)

≤ 10th Percentile	* Reconstructed annual water year discharge
≤ 25th and > 10th Percentile	**HH years (high flow in both basins)**
> 25th and < 75th Percentile	**LL years (low flow in both basins)**
≥ 75th and < 90th Percentile	**LH = Low in UCRB / High in SVT**
≥ 90th Percentile	**HL = High in UCRB / Low in SVT** *(none)*

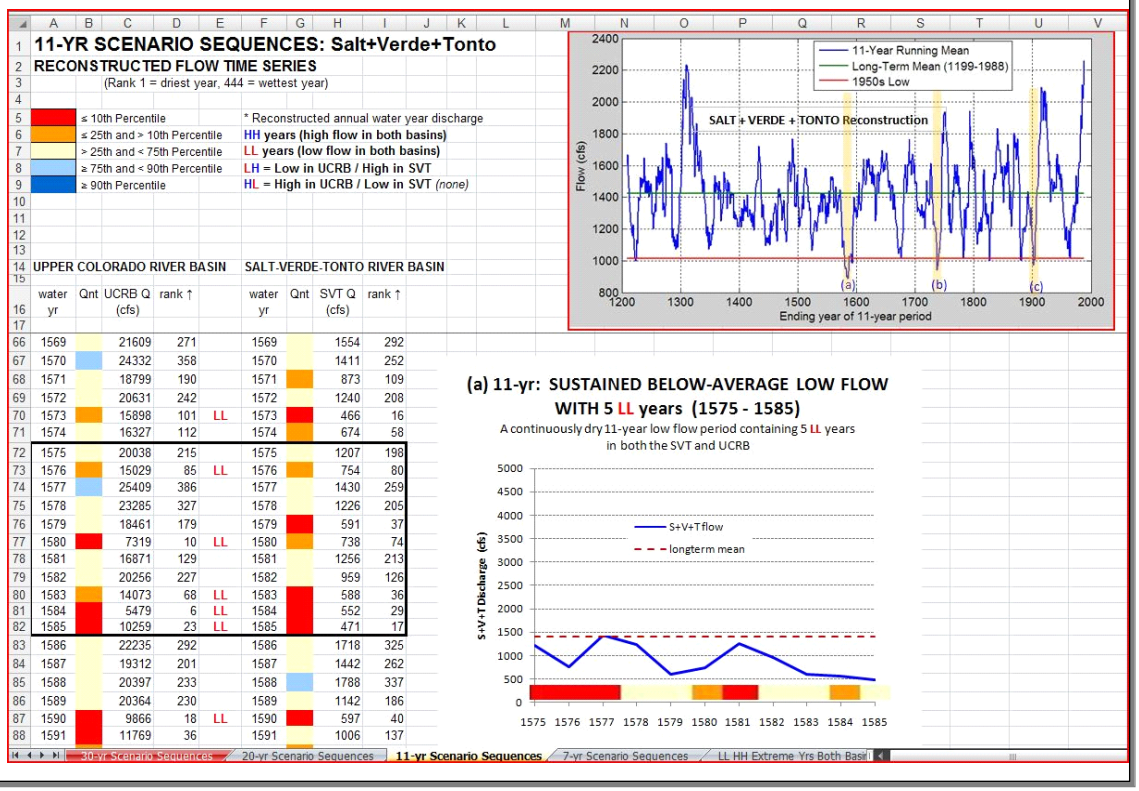
	UPPER COLORADO RIVER BASIN					SALT-VERDE-TONTO RIVER BASIN			
	water yr	Qnt	UCRB Q (cfs)	rank ↑		water yr	Qnt	SVT Q (cfs)	rank ↑
153	1656		21186	262		1656		1621	304
154	1657		24089	352		1657		903	114
155	1658		17257	141		1658		1038	152
156	1659		20493	237		1659		1356	234
157	1660		22874	312		1660		2030	372
158	1661		20729	246		1661		1896	350
159	1662		17965	164		1662		1216	200
160	1663		17131	133		1663		1391	245
161	1664		13047	52		1664		945	123
162	1665		18783	189		1665		1525	288
163	1666		14470	74	LL	1666		846	101
164	1667		10840	30	LL	1667		733	73
165	1668		13262	56	LL	1668		645	51
166	1669		21070	258		1669		840	100
167	1670		12753	49	LL	1670		477	19
168	1671		14552	75		1671		1378	241
169	1672		23367	331		1672		1519	284
170	1673		25197	381		1673		1495	270
171	1674		23020	316		1674		1399	248
172	1675		17394	144		1675		1113	174
173	1676		22916	313		1676		707	66
174	1677		21695	275		1677		1607	302
175	1678		24638	367		1678		1234	207
176	1679		22021	288		1679		1138	184
177	1680		28327	432	HH	1680		2877	429
178	1681		23311	328		1681		2238	396

LL and HH from SRP reconstructions, 1521-1964; 20-year moving average
High on Colorado R. at Lees Ferry
High on S+V+T
Low on Colorado R. at Lees Ferry
Low on S+V+T
Colorado R. at Lees Ferry
S+V+T
(a)
(b)
(c)
Mean Daily Flow (% of Normal)
Ending Year of Moving Average

(b) 20-yr: CLUSTERED SEQUENCE OF 5 LOW-FLOW YEARS WITHIN A BELOW AVERAGE DRY PERIOD (1660 - 1679)

A very dry 20-year low flow period in both the SVT and UCRB containing a 5-year sustained extreme low flow episode in both SVT & UCRB

Streamflow Sequence Spreadsheet, showing an 11-yr sequence selection



11-YR SCENARIO SEQUENCES: Salt+Verde+Tonto

RECONSTRUCTED FLOW TIME SERIES

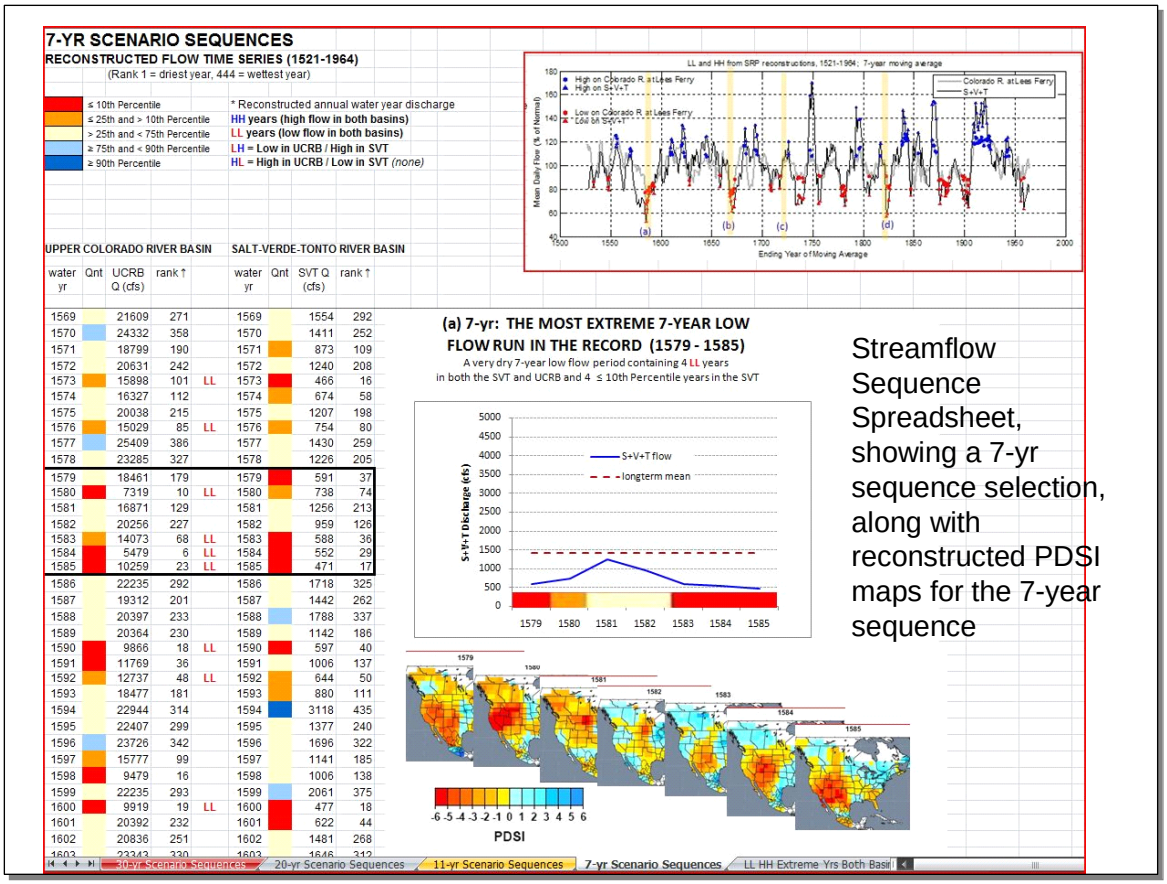
(Rank 1 = driest year, 444 = wettest year)

≤ 10th Percentile	* Reconstructed annual water year discharge
≤ 25th and > 10th Percentile	HH years (high flow in both basins)
> 25th and < 75th Percentile	LL years (low flow in both basins)
≥ 75th and < 90th Percentile	LH = Low in UCRB / High in SVT
≥ 90th Percentile	HL = High in UCRB / Low in SVT *(none)*

	UPPER COLORADO RIVER BASIN					SALT-VERDE-TONTO RIVER BASIN				
	water yr	Qnt	UCRB Q (cfs)	rank ↑		water yr	Qnt	SVT Q (cfs)	rank ↑	
66	1569		21609	271		1569		1554	292	
67	1570		24332	358		1570		1411	252	
68	1571		18799	190		1571		873	109	
69	1572		20631	242		1572		1240	208	
70	1573		15898	101	LL	1573		466	16	
71	1574		16327	112		1574		674	58	
72	1575		20038	215		1575		1207	198	
73	1576		15029	85	LL	1576		754	80	
74	1577		25409	386		1577		1430	259	
75	1578		23285	327		1578		1226	205	
76	1579		18461	179		1579		591	37	
77	1580		7319	10	LL	1580		738	74	
78	1581		16871	129		1581		1256	213	
79	1582		20256	227		1582		959	126	
80	1583		14073	68	LL	1583		588	36	
81	1584		5479	6	LL	1584		552	29	
82	1585		10259	23	LL	1585		471	17	
83	1586		22235	292		1586		1718	325	
84	1587		19312	201		1587		1442	262	
85	1588		20397	233		1588		1788	337	
86	1589		20364	230		1589		1142	186	
87	1590		9866	18	LL	1590		597	40	
88	1591		11769	36		1591		1006	137	

(a) 11-yr: SUSTAINED BELOW-AVERAGE LOW FLOW WITH 5 LL years (1575 - 1585)

A continuously dry 11-year low flow period containing 5 LL years in both the SVT and UCRB


7-YR SCENARIO SEQUENCES
RECONSTRUCTED FLOW TIME SERIES (1521-1964)
(Rank 1 = driest year, 444 = wettest year)
≤ 10th Percentile
≤ 25th and > 10th Percentile
> 25th and < 75th Percentile
≥ 75th and < 90th Percentile
≥ 90th Percentile
* Reconstructed annual water year discharge
HH years (high flow in both basins)
LL years (low flow in both basins)
LH = Low in UCRB / High in SVT
HL = High in UCRB / Low in SVT (none)
UPPER COLORADO RIVER BASIN
SALT-VERDE-TONTO RIVER BASIN
water yr
Qnt
UCRB Q (cfs)
rank ↑
SVT Q (cfs)
LL and HH from SRP reconstructions, 1521-1964; 7-year moving average
Mean Daily Flow (% of Normal)
Ending Year of Moving Average
(a) 7-yr: THE MOST EXTREME 7-YEAR LOW FLOW RUN IN THE RECORD (1579 - 1585)
A very dry 7-year low flow period containing 4 LL years
in both the SVT and UCRB and 4 ≤ 10th Percentile years in the SVT
S+V+T Discharge (cfs)
S+V+T flow
longterm mean
PDSI
1-day Scenario Sequences
20-yr Scenario Sequences
11-yr Scenario Sequences
7-yr Scenario Sequences
LL HH Extreme Yrs Both Basi

Streamflow Sequence Spreadsheet, showing a 7-yr sequence selection, along with reconstructed PDSI maps for the 7-year sequence

RANK, RECURRENCE INTERVAL, & PROBABILITIES OF FLOWS

A sample of data visualization used for analyzing the data and selecting sequences

FINAL RECONSTRUCTED FLOW TIME SERIES (in cfs)

(Rank 1 = driest year, 444 = wettest year)

UPPER COLORADO RIVER BASIN at Lees Ferry								SALT-VERDE-TONTO RIVER BASIN						
water yr	Qnt	UCRB Q (cfs)	rank ↑	RI	P	1-P		water yr	Qnt	SVT Q (cfs)	rank ↑	RI	P	1-P
1640		25113.56	377	1.180	0.847	0.153	HH	1640		2366.54	407	1.093	0.915	0.085
1641		20093.47	220	2.023	0.494	0.506		1641		1956.70	360	1.236	0.809	0.191
1642		21896.08	285	1.561	0.640	0.360		1642		1509.09	277	1.606	0.622	0.378
1643		22686.10	306	1.454	0.688	0.312		1643		1339.20	228	1.952	0.512	0.488
1644		20223.18	224	1.987	0.503	0.497		1644		2087.03	377	1.180	0.847	0.153
1645		15115.95	88	5.057	0.198	0.802		1645		1150.97	190	2.342	0.427	0.573
1646		14710.00	76	5.855	0.171	0.829		1646		1414.62	255	1.745	0.573	0.427
1647		24041.50	350	1.271	0.787	0.213	HH	1647		1928.99	357	1.246	0.802	0.198
1648		15188.17	90	4.944	0.202	0.798	LL	1648		553.03	30	14.833	0.067	0.933
1649		24971.73	374	1.190	0.840	0.160		1649		1717.89	326	1.365	0.733	0.267
1650		23284.62	326	1.365	0.733	0.267		1650		1976.37	363	1.226	0.816	0.184
1651		23541.10	337	1.320	0.757	0.243	HH	1651		2834.84	428	1.040	0.962	0.038
1652		17646.93	155	2.871	0.348	0.652		1652		1409.52	251	1.773	0.564	0.436
1653		12641.67	46	9.674	0.103	0.897		1653		914.95	116	3.836	0.261	0.739
1654		5110.52	2	222.500	0.004	0.996	LL	1654		503.33	22	20.227	0.049	0.951
1655		27720.94	428	1.040	0.962	0.038		1655		1692.76	321	1.386	0.721	0.279
1656		21186.05	262	1.698	0.589	0.411		1656		1620.74	304	1.464	0.683	0.317
1657		24088.94	352	1.264	0.791	0.209		1657		903.16	114	3.904	0.256	0.744
1658		17257.24	141	3.156	0.317	0.683		1658		1037.80	152	2.928	0.342	0.658
1659		20493.09	237	1.878	0.533	0.467		1659		1356.00	234	1.902	0.526	0.474
1660		22874.49	312	1.426	0.701	0.299		1660		2029.66	372	1.196	0.836	0.164
1661		20728.99	246	1.809	0.553	0.447		1661		1895.67	350	1.271	0.787	0.213
1662		17965.35	164	2.713	0.369	0.631		1662		1216.38	200	2.225	0.449	0.551
1663		17130.55	133	3.346	0.299	0.701		1663		1390.97	245	1.816	0.551	0.449
1664		13046.53	52	8.558	0.117	0.883		1664		944.79	123	3.618	0.276	0.724
1665		18783.42	189	2.354	0.425	0.575		1665		1524.60	288	1.545	0.647	0.353
1666		14469.66	74	6.014	0.166	0.834	LL	1666		845.74	101	4.406	0.227	0.773
1667		10840.19	30	14.833	0.067	0.933	LL	1667		732.93	73	6.096	0.164	0.836
1668		13261.72	56	7.946	0.126	0.874	LL	1668		644.71	51	8.725	0.115	0.885
1669		21069.88	258	1.725	0.580	0.420		1669		840.23	100	4.450	0.225	0.775
1670		12753.19	49	9.082	0.110	0.890	LL	1670		477.50	19	23.421	0.043	0.957
1671		14552.04	75	5.933	0.169	0.831		1671		1377.62	241	1.846	0.542	0.458
1672		23366.90	331	1.344	0.744	0.256		1672		1518.59	284	1.567	0.638	0.362
1673		25197.15	381	1.168	0.856	0.144		1673		1495.31	270	1.648	0.607	0.393
1674		23019.89	316	1.408	0.710	0.290		1674		1398.53	248	1.794	0.557	0.443
1675		17394.45	144	3.090	0.324	0.676		1675		1112.52	174	2.557	0.391	0.609
1676		22915.91	313	1.422	0.703	0.297		1676		707.25	66	6.742	0.148	0.852
1677		21695.46	275	1.618	0.618	0.382		1677		1607.24	302	1.474	0.679	0.321
1678		24638.13	367	1.213	0.825	0.175		1678		1233.59	207	2.150	0.465	0.535
1679		22020.52	288	1.545	0.647	0.353		1679		1138.43	184	2.418	0.413	0.587
1680		28327.11	432	1.030	0.971	0.029	HH	1680		2877.31	429	1.037	0.964	0.036
1681		23310.67	328	1.357	0.737	0.263		1681		2237.87	396	1.124	0.890	0.110

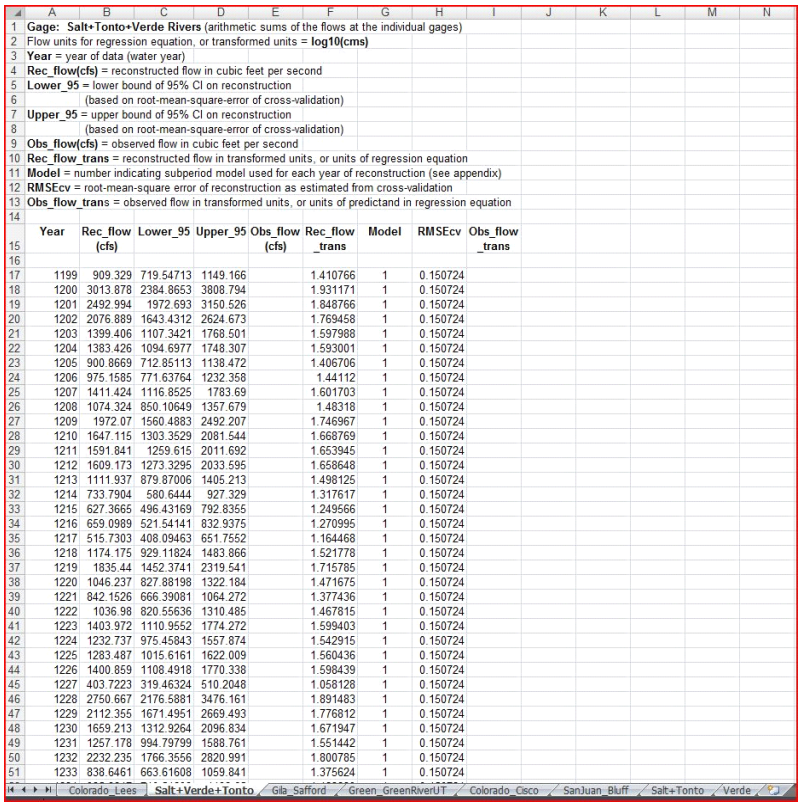
Another way of looking at the reconstruction data – sorted by magnitude

FINAL RECONSTRUCTED FLOW SORTED BY MAGNITUDE (lowest => highest)

(Rank 1 = driest year, 444 = wettest year)

UPPER COLORADO RIVER BASIN at Lees Ferry							SALT-VERDE-TONTO RIVER BASIN						
water yr	Qnt	UCRB Q (cfs)	rank ↑	RI	P	1-P	water yr	Qnt	SVT Q (cfs)	rank ↑	RI	P	1-P
1685		4344.24	1	445.000	0.002	0.998	1748		252.20	1	445.000	0.002	0.998
1654		5110.52	2	222.500	0.004	0.996	1847		349.04	2	222.500	0.004	0.996
1542		5252.23	3	148.333	0.007	0.993	1904		358.73	3	148.333	0.007	0.993
1845		5331.27	4	111.250	0.009	0.991	1542		369.57	4	111.250	0.009	0.991
1532		5439.72	5	89.000	0.011	0.989	1818		390.85	5	89.000	0.011	0.989
1584		5478.70	6	74.167	0.013	0.987	1773		398.95	6	74.167	0.013	0.987
1902		5851.49	7	63.571	0.016	0.984	1861		402.71	7	63.571	0.016	0.984
1851		6278.93	8	55.625	0.018	0.982	1822		403.09	8	55.625	0.018	0.982
1934		7103.86	9	49.444	0.020	0.980	1735		409.12	9	49.444	0.020	0.980
1580		7318.60	10	44.500	0.022	0.978	1685		416.99	10	44.500	0.022	0.978
1871		8147.17	11	40.455	0.025	0.975	1899		450.73	11	40.455	0.025	0.975
1735		8362.28	12	37.083	0.027	0.973	1951		451.47	12	37.083	0.027	0.973
1879		8465.68	13	34.231	0.029	0.971	1729		456.66	13	34.231	0.029	0.971
1798		8809.75	14	31.786	0.031	0.969	1902		457.25	14	31.786	0.031	0.969
1847		9346.58	15	29.667	0.034	0.966	1752		461.00	15	29.667	0.034	0.966
1598		9479.32	16	27.813	0.036	0.964	1573		465.80	16	27.813	0.036	0.964
1954		9636.30	17	26.176	0.038	0.962	1585		471.47	17	26.176	0.038	0.962
1590		9865.99	18	24.722	0.040	0.960	1600		477.13	18	24.722	0.040	0.960
1600		9918.93	19	23.421	0.043	0.957	1670		477.50	19	23.421	0.043	0.957
1607		10062.48	20	22.250	0.045	0.955	1728		481.65	20	22.250	0.045	0.955
1773		10093.45	21	21.190	0.047	0.953	1522		501.99	21	21.190	0.047	0.953
1824		10187.69	22	20.227	0.049	0.951	1654		503.33	22	20.227	0.049	0.951
1585		10259.44	23	19.348	0.052	0.948	1623		523.51	23	19.348	0.052	0.948
1748		10371.31	24	18.542	0.054	0.946	1819		529.26	24	18.542	0.054	0.946
1729		10441.82	25	17.800	0.056	0.944	1632		531.10	25	17.800	0.056	0.944
1861		10490.94	26	17.115	0.058	0.942	1900		531.80	26	17.115	0.058	0.942
1896		10545.53	27	16.481	0.061	0.939	1871		541.53	27	16.481	0.061	0.939
1686		10743.12	28	15.893	0.063	0.937	1959		545.33	28	15.893	0.063	0.937
1855		10768.92	29	15.345	0.065	0.935	1584		552.24	29	15.345	0.065	0.935
1667		10840.19	30	14.833	0.067	0.933	1648		553.03	30	14.833	0.067	0.933
1756		11152.62	31	14.355	0.070	0.930	1820		556.37	31	14.355	0.070	0.930
1959		11303.87	32	13.906	0.072	0.928	1684		564.67	32	13.906	0.072	0.928
1887		11368.20	33	13.485	0.074	0.926	1785		568.53	33	13.485	0.074	0.926
1545		11558.23	34	13.088	0.076	0.924	1842		573.82	34	13.088	0.076	0.924
1632		11580.02	35	12.714	0.079	0.921	1780		574.92	35	12.714	0.079	0.921
1591		11768.75	36	12.361	0.081	0.919	1583		588.20	36	12.361	0.081	0.919
1531		11770.96	37	12.027	0.083	0.917	1579		591.08	37	12.027	0.083	0.917
1736		11866.41	38	11.711	0.085	0.915	1829		593.00	38	11.711	0.085	0.915

Streamflow reconstruction spreadsheet with annotated data sets for all watersheds



Gage: Salt+Tonto+Verde Rivers (arithmetic sums of the flows at the individual gages)
Flow units for regression equation, or transformed units = **log10(cms)**
Year = year of data (water year)
Rec_flow(cfs) = reconstructed flow in cubic feet per second
Lower_95 = lower bound of 95% CI on reconstruction
(based on root-mean-square-error of cross-validation)
Upper_95 = upper bound of 95% CI on reconstruction
(based on root-mean-square-error of cross-validation)
Obs_flow(cfs) = observed flow in cubic feet per second
Rec_flow_trans = reconstructed flow in transformed units, or units of regression equation
Model = number indicating subperiod model used for each year of reconstruction (see appendix)
RMSEcv = root-mean-square error of reconstruction as estimated from cross-validation
Obs_flow_trans = observed flow in transformed units, or units of predictand in regression equation

Year	Rec_flow (cfs)	Lower_95	Upper_95	Obs_flow (cfs)	Rec_flow _trans	Model	RMSEcv	Obs_flow _trans
1199	909.329	719.54713	1149.166		1.410766	1	0.150724	
1200	3013.878	2384.8653	3808.794		1.931171	1	0.150724	
1201	2492.994	1972.693	3150.526		1.848766	1	0.150724	
1202	2076.889	1643.4312	2624.673		1.769458	1	0.150724	
1203	1399.406	1107.3421	1768.501		1.597988	1	0.150724	
1204	1383.426	1094.6977	1748.307		1.593001	1	0.150724	
1205	900.8669	712.85113	1138.472		1.406706	1	0.150724	
1206	975.1585	771.63764	1232.358		1.44112	1	0.150724	
1207	1411.424	1116.8525	1783.69		1.601703	1	0.150724	
1208	1074.324	850.10649	1357.679		1.48318	1	0.150724	
1209	1972.07	1560.4883	2492.207		1.746967	1	0.150724	
1210	1647.115	1303.3529	2081.544		1.668769	1	0.150724	
1211	1591.841	1259.615	2011.692		1.653945	1	0.150724	
1212	1609.173	1273.3295	2033.595		1.658648	1	0.150724	
1213	1111.937	879.87006	1405.213		1.498125	1	0.150724	
1214	733.7904	580.6444	927.329		1.317617	1	0.150724	
1215	627.3665	496.43169	792.8355		1.249566	1	0.150724	
1216	659.0989	521.54141	832.9375		1.270995	1	0.150724	
1217	515.7303	408.09463	651.7552		1.164468	1	0.150724	
1218	1174.175	929.11824	1483.866		1.521778	1	0.150724	
1219	1835.44	1452.3741	2319.541		1.715785	1	0.150724	
1220	1046.237	827.88198	1322.184		1.471675	1	0.150724	
1221	842.1526	666.39081	1064.272		1.377436	1	0.150724	
1222	1036.98	820.55636	1310.485		1.467815	1	0.150724	
1223	1403.972	1110.9552	1774.272		1.599403	1	0.150724	
1224	1232.737	975.45843	1557.874		1.542915	1	0.150724	
1225	1283.487	1015.6161	1622.009		1.560436	1	0.150724	
1226	1400.859	1108.4918	1770.338		1.598439	1	0.150724	
1227	403.7223	319.46324	510.2048		1.058128	1	0.150724	
1228	2750.667	2176.5881	3476.161		1.891483	1	0.150724	
1229	2112.355	1671.4951	2669.493		1.776812	1	0.150724	
1230	1659.213	1312.9264	2096.834		1.671947	1	0.150724	
1231	1257.178	994.79799	1588.761		1.551442	1	0.150724	
1232	2232.235	1766.3556	2820.991		1.800785	1	0.150724	
1233	838.6461	663.61608	1059.841		1.375624	1	0.150724	

Colorado_Lees | Salt+Verde+Tonto | Gila_Safford | Green_GreenRiverUT | Colorado_Cisco | SanJuan_Bluff | Salt+Tonto | Verde

Appendix B

Nimue beta

3D MODFLOW VISUALIZER

DECISION THEATER™
ARIZONA STATE UNIVERSITY

ASU ARIZONA STATE UNIVERSITY
IRA A. FULTON SCHOOL OF ENGINEERING
HIGH PERFORMANCE COMPUTING

Nimue - 3D MODFLOW Visualizer

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1 Introduction to Nimue beta

WELCOME TO NIMUE beta

Nimue (pronounced nee-moo-wey) is an open source visualization software package designed to view groundwater modeling data outputted from MODFLOW, the hydrogeology industry standard software for groundwater modeling. Nimue is designed specifically for managers and decision makers. Today's software products available for viewing MODFLOW data sets require the technical skills of a hydrologist. Usually this is not problematic because a hydrologist is using the same software for modeling groundwater scenarios as it is to present the results.

Working with local and regional water managers in central Arizona has shown that a more intuitive viewer which facilitates policy decision making is important when a regional stakeholder group is looking at various scenarios. A user-friendly visualization can provide decision makers a flexible venue for investigating scientific information. Furthermore, the 3D capabilities provided in this framework allow stakeholders of all backgrounds to understand the information in ways that are not available in today's commercial viewers.

Nimue Quick Facts:

- Easy viewing and navigation in three dimensions of MODFLOW data
- Ability to import geographic data
- Animation feature runs through time steps of data
- Interactive cross-section generation that cuts across data surfaces
- Convenient creation of 3D fly-through of data
- Quick export of images from viewer

Hardware Requirements

Nimue is a sophisticated software visualization package and therefore requires a computer with 3D rendering capabilities.

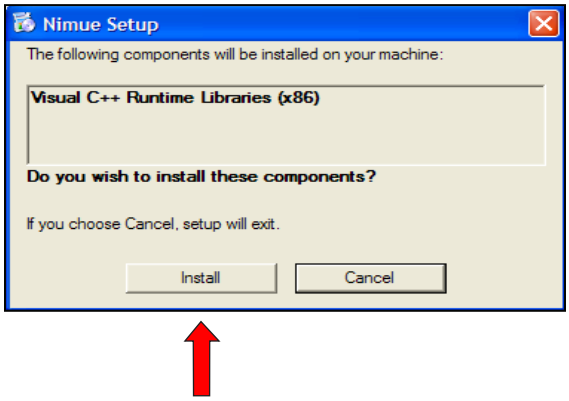
Recommended system hardware:

- Intel Dual Pentium 4 2.6GHz or faster
- 1GB RAM
- 256 MB 3D graphics card
- Microsoft Windows XP or later
- CD-ROM drive (for installation disc)
- 65 MB disk space (not including MODFLOW files)

INSTALLATION GUIDE

The following steps detail the installation instructions for Nimue.

- Insert the Nimue CD-ROM into your computer.
- Double click “My Computer”, and then double click on your CD drive icon to view the disc contents.
- Double click the “Nimue.exe” file to begin the installation process.
- This will automatically launch the WinZip Self-Extractor program.

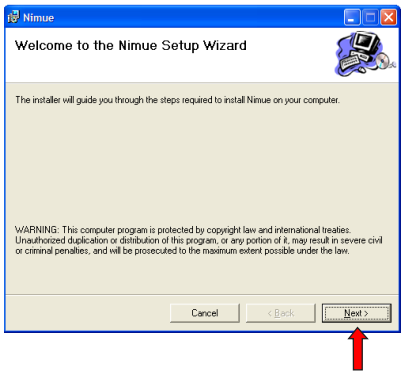

Nimue Setup
The following components will be installed on your machine:
Visual C++ Runtime Libraries (x86)
Do you wish to install these components?
If you choose Cancel, setup will exit.
Install
Cancel

- When prompted to install the “Visual C++ Runtime Libraries”, choose install. This is necessary to enable Nimue to run.

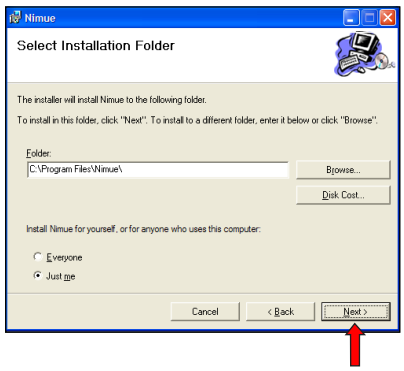
"WELCOME TO THE NIMUE SETUP WIZARD"

The following steps will complete the Nimue installation on your computer.

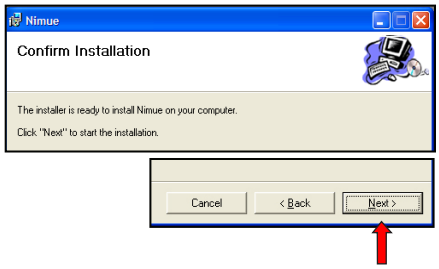
- After the Visual C++ Runtime Libraries have been installed, the Nimue Setup Wizard will open. Click on "Next" to continue.


Nimue
Welcome to the Nimue Setup Wizard
The installer will guide you through the steps required to install Nimue on your computer.
WARNING: This computer program is protected by copyright law and international treaties. Unauthorized duplication or distribution of this program, or any portion of it, may result in severe civil or criminal penalties, and will be prosecuted to the maximum extent possible under the law.
Cancel
< Back
Next >

- Choose a location to install the program to. The default location will install to your Program Files. Click on "Browse" to change the install location.
- You can also choose which accounts on your computer can use Nimue by switching the "Everyone" or "Just Me" option.


Nimue
Select Installation Folder
The installer will install Nimue to the following folder.
To install in this folder, click "Next". To install to a different folder, enter it below or click "Browse".
Folder:
C:\Program Files\Nimue\
Browse...
Disk Cost...
Install Nimue for yourself, or for anyone who uses this computer:
Everyone
Just me
Cancel
< Back
Next >

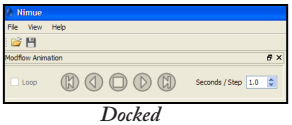
- The final step is to choose "Next" when the "Confirm Installation" screen pops up.


Nimue
Confirm Installation
The installer is ready to install Nimue on your computer.
Click "Next" to start the installation.
Cancel
< Back
Next >

- This completes the installation of Nimue on your computer.

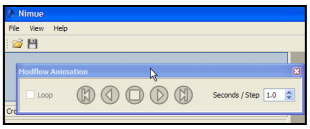
2 Getting Started

The MODFLOW environment essentially has two sections: the main viewing window and many small modules that perform specific functions. These modules are "dockable", meaning they can be moved and adjusted to fit the needs of a particular session. Because of this, modules can be scaled down to fit on smaller screens, or removed altogether.



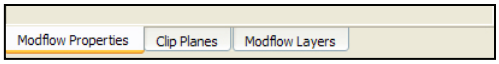
Docked

To move a module window, click and drag the module window title bar until the window snaps out of place. When the module is moved over space that it can dock to the space below will be highlighted in blue. Modules can remain independent of other docked windows if moved to an open space on the screen.



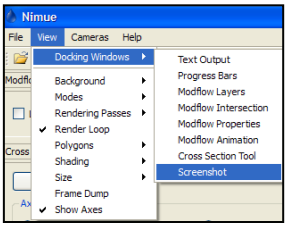
Un-docked

MODFLOW modules can also be arranged in tabs, making organization easier and free up window space.
To create a module tab, drag the window over the same space as another module until the space below is highlighted in blue. Releasing the window will automatically dock the module. This process can easily be reversed by dragging the desired module away from its current position.



Tabs

Closing module windows will remove them from the current session. At any point however, module windows can be returned by navigating the "View" menu and selecting "Docking Windows".



Docking Windows Menu

NAVIGATION:

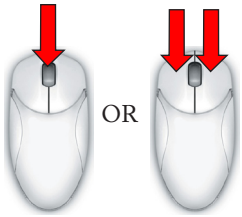
Mouse Controls:

Left mouse button:

Click and hold to rotate the entire model around a center axis.

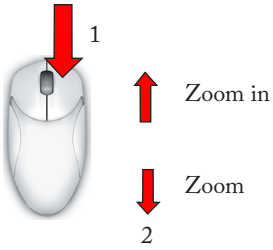
Middle mouse button OR both mouse buttons:

Click and hold the middle mouse button or click and hold both the left and right buttons to "grab" and move the model along a single axis.



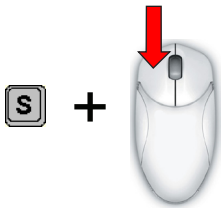
Right mouse button:

Click and hold, then move mouse forward or backward to zoom in/out.



"S" key plus left mouse button:

Push the "s" key then click and hold the left mouse button to define a new center location for the rotation axis. Press "f" to return to the default center location.



Key Commands:

Arrow Keys - Rotates the scene 45 in the direction pressed.

Spacebar - Resets the camera orientation to the default position. X axis will move to a horizontal position. The zoom level is not changed when spacebar is pushed.

F – Returns model to default view. (Must be pressed once after loading new MODFLOW file to bring the model into view)

H – Toggles the wire frame and shaded rendering settings together.

P - Toggles the points rendering view on or off.

W – Toggles the wire frame view mode on or off.

IMPORTING DATA:

From the file menu you can open existing Nimue projects, or create a new project by choosing

- File > New > MODFLOW Document

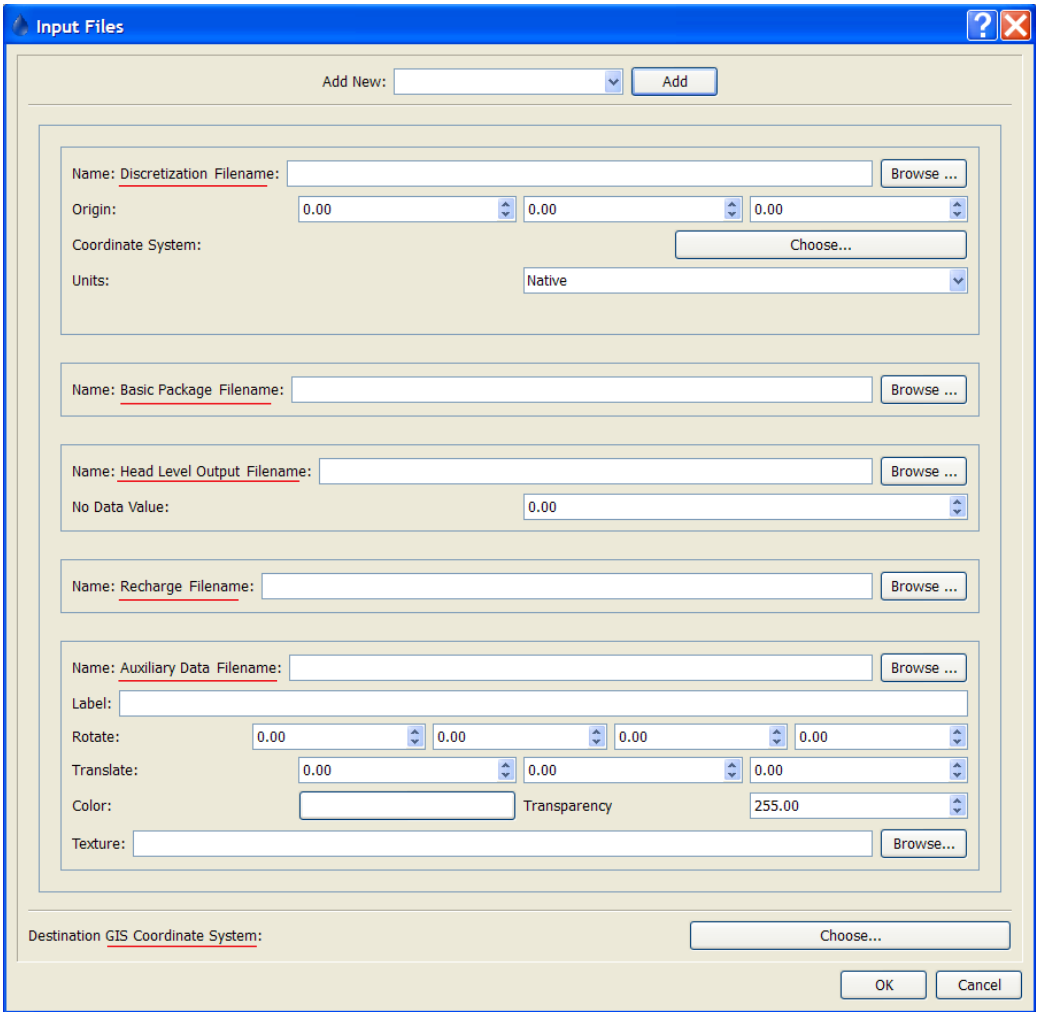
or

- File > Scene > Document

Nimue models are built from a combination of different MODFLOW data sets. These include:

- Discretization files (.dis)
- Basic Package files (.ba6)
- Head Level Output files
- Recharge file (.rch)
- Auxiliary Data
- GIS Coordinate System

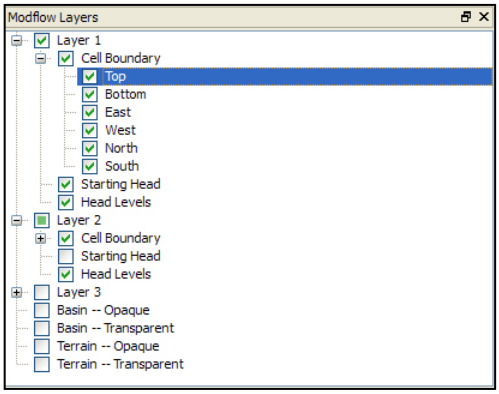
Descriptions of each of these file types can be found in Chapter 4.



MODULES

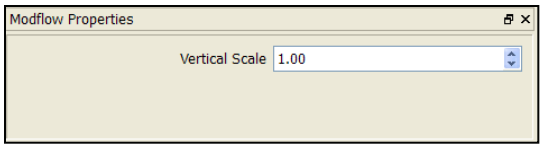
MODFLOW Layers (Table of Contents):

The "MODFLOW Layers" window allows you to toggle which data sets to view on and off. Top level layers can be expanded to view their contents by clicking on the + box. Each sub-layer can be turned on or off by clicking the box beside the name.



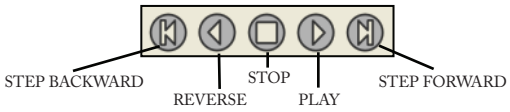
MODFLOW Properties:

Vertical Scale: Set the vertical scale for terrain in your model. Units correspond to settings found in the loaded MODFLOW data. Scale is from 1-99.



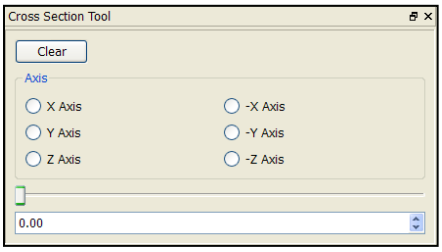
MODFLOW Animation:

The animation module serves as the controls for animation sets found in the loaded MODFLOW data. The buttons function much like a video player. Time steps for animations can be seen at the bottom left of the scene window.



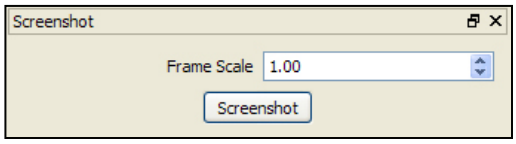
Cross Section Tool:

This function allows you to slice your models to create cross-sectional views of your data. Choose the axis from which you want to cut the model using the radio buttons, then enter the appropriate UTM coordinate in the box or move the slide bar to create a rectangular plane that intersects the model.



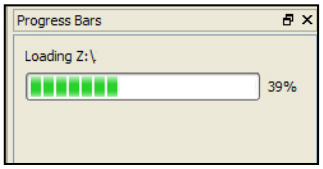
Screen shot:

This function will create a screen capture of the scene. Once you click "Screenshot", a window will pop up that allows you to create a file name and navigate to the correct directory where you can save the document. You can save screen captures as .bmp, .jpeg, and .png files. The Frame Scale option will multiply the resolution by the selected factor. While you can choose a scale from 1-99, images scaled larger than a factor of 10 may be too large to export.



Progress Bars:

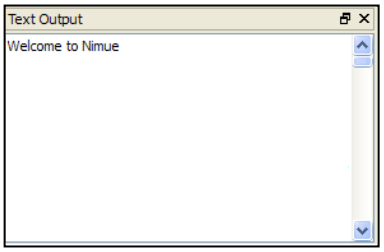
When loading a file, this window provides visual feedback on the progress. This can come in handy when dealing with particularly large data sets. When no files are being loaded, this window will appear empty.



Text Output:

This window provides program status. Examples of typical messages include:

- MODFLOW data loading status
- Software version information
- Availability of plug-ins
- Error messages



3 Operations

FILE MENU

New:

- MODFLOW Document - This opens the import dialog.
- Scene Document - Opens a blank scene. Drag and drop OSG files onto the new scene to load.

Open:

Use when loading existing MODFLOW documents.

Save/Save As:

Export:

- Image - Exports the scene as a raster. (.jp g, .bmp, .png, .rgba)
- Model - Exports all data into the native file formats for Open Scene Graph. (.ive, .osg)
- Scene - If you are including a cross section that cuts your model data and wish to preserve this in the exported model, select "export scene". This option exports model data in the native file formats for Open Scene Graph. (.ive, .osg)

VIEW MENU

Background:

Use this option to change the color shading of your background. Selecting different colors for different corners will create gradient shades between them.

Modes:

Navigate: The default navigation with mouse control.

Pick: Enables the use of the right mouse button to bring up an options menu.

Seek: Centers the scene where the mouse is clicked.

Rendering Passes:

This selection increases the resolution of the output screen shots from the Frame Dump option. A higher number will create more instances of exported frames.

Render Loop:

Render Loop allows for continuous redrawing of the scene. This function is only necessary when using Open Scene Graph documents, and therefore does not apply to MODFLOW data.

Polygons:

Specifies how polygons in the model will appear

- Filled – the default setting where all features are visible
- Hidden Lines – Turns off filled polygons to show hidden lines and removes shading
- Wire Frame – Switches to viewing only polygon vertices and their connecting lines
- Points – Switches to showing only polygon vector points.

Shading:

Changes the triangle size of the terrain layer. Smooth renders terrain polygons at a fine level, and flat will reduce the terrain to a course level.

Size:

Choose from several common resolution settings for the render window, or enter a custom window size.

Frame Dump:

Frame Dump will export an image continuously to a defined location on your computer. The Rendering Passes menu controls how often the scene image is saved. To begin the process, click "Frame Dump" in the View menu. The Text Output module will display the image file currently being written. To stop the process, choose "Frame Dump" again. It should be noted that if the Frame Dump process is left on, files will be written to the hard drive until no space remains. The appropriate location to save frames should be outside of the Nimue program folder. Additionally, make sure the folder you choose to save frames to does not contain spaces in the name. For example, "SaveFrames", not "Save Frames".

Show Axes:

Toggles the view of the X, Y, and Z axis in the lower left corner of the scene.

CAMERAS

The camera menu functions allow the user to save specific views of their data loaded in the window. This function is useful for saving perspectives that highlight elements of your data. Each camera path can store many perspective views. The collection of perspective shots can further be used to generate flights between perspective views. These functions can be particularly useful for presenting data.

New Path

Creates a new blank camera file with the extension *.cpf. In order to create new camera paths, you must first click "New Path." When you have set the correct perspective view in the window that you want to save, click "Append." Clicking Append saves the first camera in your new Camera Path.

Once you have appended a new view to the camera path, you can go back to that view by navigating to "Cameras" in the menu. The first perspective saved will be called "Camera 0". The next camera view saved will be called "Camera 1".

Open Path

If you have existing camera paths saved with the extension *.cpf, you may open that file by clicking "Open Path" and navigating to the directory where you have saved your *.cpf file.

Save Path

Once you have created a camera path using "New Path" it will not be saved unless you click "Save Path." You may navigate to anywhere you would like to store your *.cpf file.

Save Path As

You may save your camera paths either by clicking "Save Path" or "Save Path As." Using "Save Path As" allows the user to save a new camera path or existing camera path as another name or in another directory.

Export Movie

This function is currently grayed out and will be available in Nimue 2.0.

Append

Use Append to create a new camera view to be saved in your camera path. Each time you use Append, it will create a new camera view and append it to the list of cameras in the "Cameras" drop down.

Prepend

Use Prepend to create a new camera view to be saved in your camera path. Each time you use Prepend, it will create a new camera view and add it to the beginning of the list of cameras in the "Cameras" drop down.

Close

The Close function adds a camera to the end of your list of camera views that is identical to your first camera view, Camera 0. This function is useful when using the "Play Forward" and "Play Backward" functions.

Play Forward

When clicking on "Play Forward" the scene will animate by flying from camera to camera in your set of camera views. "Play Forward" will run from Camera 0 to the end of your list in order.

Play Backward

When clicking on "Play Backward" the scene will animate by flying from camera to camera in your set of camera views. "Play Backward" will run from your last Camera to Camera 0 in reverse order.

Stop

The Stop menu will only be active when Nimue is in Play Forward or Play Backward. It will stop the flight between camera views at any time.

Degree

Degree determines the nature of flight between cameras when using Play Forward or Play Backward. For example, 1 = linear flight path, 3= cubic flight path. Experiment with these options to find your preference for flying between cameras.

Step Size

This function controls the speed of flight between cameras. The numbers represent relative speeds of flight between one camera to another.

Camera Paths

If you have opened more than one *.cpf document, you can switch between them by checking them in the Camera Paths drop down.

HELP

The Help menu contains a link that will open this user manual.

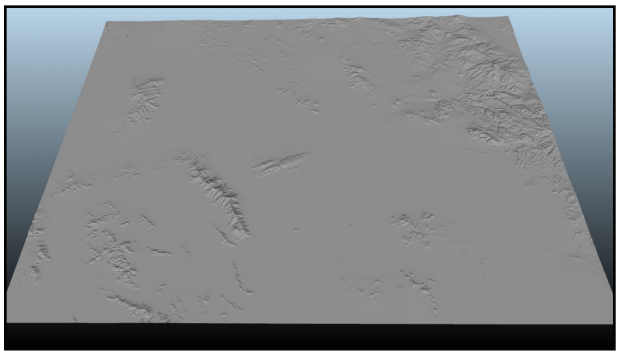
4 Model Data

GEOGRAPHIC DATA

The follow paragraphs identify and describe the MODFLOW file types recognized by Nimue. Nimue was developed to accept MODFLOW 2000 free-format files. Other file formats are not recommended.

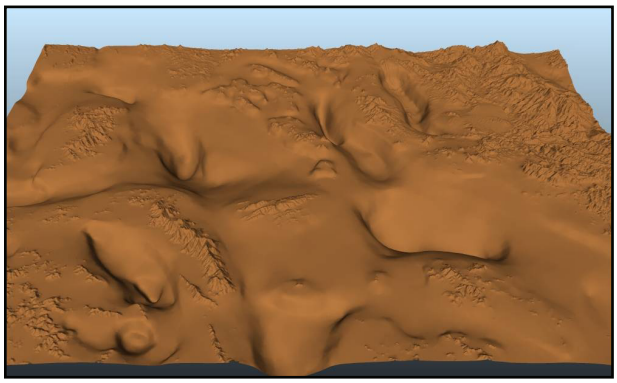
Terrain

Included in this version of Nimue is the topographic of the Salt River Valley in central Arizona, originally obtained from the US Geological Survey Seamless website (http://seamless.usgs.gov) as a digital elevation model (DEM). It has been converted into an OpenSceneGraph file here.



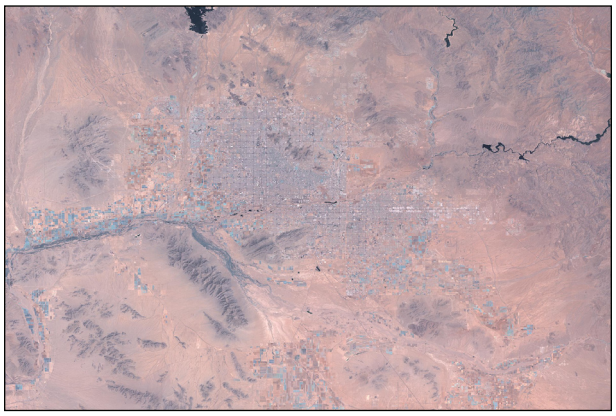
Subsurface Bedrock

Included in this version of Nimue is the subsurface bedrock topography expressing the basin and range topography of the Salt River Valley. The data originates from Oppenheimer and Sumner (1980). This data was processed using ArcMap and ArcScene to convert vector contours into a raster surface, and then merged to the surface bedrock from the USGS DEM by Jessica Block. It was then converted into an OpenSceneGraph file.



Imagery

Included in this version of Nimue is the 2005 LANDSAT imagery from NASA's Onearth website (http://onearth.jpl.nasa.gov/). It is being used as the texture for the terrain listed above. Overlaying the imagery are the major highways through central Arizona.



Surface Water Canals

One of the key components to water use is water delivery infrastructure. Nimue includes vector line files for the surface water canals of the Salt River Valley including the canals for CAP and SRP. This data comes from the Arizona Water Banking Authority GIS Database for Phoenix and Tucson Active Management Areas.

Recharge Locations

This point data set includes most of the recharge locations in the Salt River Valley. This data set also comes from the Arizona Water Banking Authority GIS Database for Phoenix and Tucson Active Management Areas.

MODFLOW FILE DESCRIPTIONS

Nimue supports the following MODFLOW documents:

Discretization File (SRV model extension *.dis):

Nimue reads the number of model layers and the cell rows and columns. Additionally it extracts a conversion constant that provides the appropriate distance units. It also assigns the thickness of every layer by defining the model surface elevation, bottom of layer 1 (Upper Alluvial Unit), bottom of layer 2 (Middle Alluvial Unit), and bottom of layer 3 (Lower Alluvial Unit) for every active cell.

Basic File (SRV model extension *.ba6):

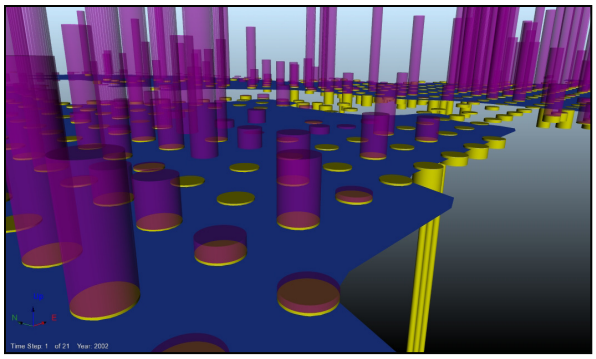
Defines the active model array and the starting heads.

Block-Centered Flow File (BCF) (SRV model extension: *.bc6)

Defines the model layer type, turns on rewriting capability, and assigns hydraulic properties to each active model cell. The layer type flag in the BCF package defines how the transmissivity for each model cell is calculated. The hydraulic conductivity, primary and secondary storage (when applicable), and the vertical hydraulic conductivity (Vcont) are assigned using the BCF package.

Well File (SRV model extension *.wel)

Simulates pumpage, recharge, and groundwater flux into and out of the model for each stress period. Negative values represent well pumpage that is distributed by cell and layer or estimated groundwater underflow out of the model along selected model boundaries. Positive pumpage values represent specified mountain front recharge, ephemeral stream recharge, and underflow into the model along some of the model boundaries. This file is known by Nimue as the "pumping" and is added to the MODFLOW layers view by listing in each layer that has associated. It is displayed in Nimue by vertical cylinders. Water being taken out of the ground is represented by cylinders pointing up. Recharge is represented by cylinders pointing below the land surface. When importing a pumping file, the user may choose which color to display the cylinders.



Example recharge and well data. The purple cylinders indicate well data pumpage volume and the yellow cylinders indicate recharge volume.

Recharge File (SRV model extension *.rch)

The Recharge file applies aerial recharge to cells within the model. The source of aerial recharge includes natural recharge (mountain-front and stream infiltration) and incidental recharge (agricultural, artificial, and urban). Recharge cylinders are represented by cylinders pointing below the land surface.

REFERENCES

Corkhill, E.F. and S. Corell, A Regional Groundwater Flow Model of the Salt River Valley – Phase I, Phoenix Active Management Area, Hydrogeologic Framework and Basic Data Report, Modeling Report No. 6, Arizona Department of Water Resources, 1993.

Corell, S.W. and E.F. Corkhill, A Regional Groundwater Flow Model of the Salt River Valley – Phase II; Phoenix Active Management Area, Numerical Model, Calibration, and Recommendations, Modeling Report No. 8, Arizona Department of Water Resources, 1994.

Gray, S.T., Bettancourt, J.L., Fastie, C.L., and Jackson, S.T., Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains, Geophysical Research Letters, 30(6), pp.49-49, 2003.

Oppenheimer, J.M., and J.S. Sumner, Depth-to-Bedrock Map, Basin and Range Province, Arizona, scale 1:1,000,000, Laboratory of Geo physics, University of Arizona, 1980.

US Bureau of Reclamation, Arizona Water Banking Authority GIS Database for Phoenix and Tucson Active Management Areas, 2004.

US Geological Survey, 30-meter Digital Elevation Model, Seamless Website: http://seamless.usgs.gov